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Post-Consumer Waste Wood in Attributive Product LCA

Context specific evaluation of allocation procedures in a functionalistic conception of LCA

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Abstract

Background. In product life cycle assessment (LCA), the attribution of environmental interventions to a product under study is an ambiguous task. This is due to a) the simplistic modeling characteristics in the life cycle inventory step (LCI) of LCA in view of the complexity of our techno-economic system, and b) to the non-tangible theoretical nature of the product system as a representation of the processes 'causally' linked to a product. Ambiguous methodological decisions during the setup of an LCI include the modeling of end-of-life scenarios or the choice of an allocation factor for the allocation of joint co-production processes. An important criterion for methodological decisions – besides the conformity with the relevant series of standards ISO 14 040 – is if the improvement options, which can be deduced from the LCI, are perceived by the decision-maker as to redirect the material flows at stake into more sustainable paths.

Methods. From this functionalistic conception of LCA, this article develops a set of wood-specific requirements, an LCI of wood products has to fulfill to give adequate decision support under Central European conditions. These requirements serve as a basis for the evaluation of different allocation procedures in a case study related to the modeling of end-of-life scenarios in a product LCA of wood products. The case study discusses how the recycling and incineration of a creosote-treated railway sleeper (*Am.* tie) are modeled according to various methodological propositions for the solution of the allocation problems related to recycling and final disposal. A partial life cycle model of the railway sleeper demonstrates the effect of the different allocation procedures to the over-all result.

Results and Discussion. The most important conclusion – apart from proposing a functionalistic approach to solve allocation problems – is that under Central European conditions both the material and energy aspects of wood and the related substitution and opportunity effects (opportunity 'cost') should be considered for the modeling of post-consumer waste wood in attributive product LCA, even when comparing products made of different materials.

Keywords: Allocation final; disposal; life cycle assessment; opportunity effects; post-consumer waste wood; railway sleeper; recycling; substitution; wood

1 Introduction

In product life cycle assessment (LCA), the attribution of environmental interventions to a product under study is an ambiguous task. Ambiguous methodological decisions during the setup of an LCI include the modeling of end-of-life scenarios or the choice of an allocation factor for the allocation of joint co-production processes. An important criterion for methodological decisions – besides the conformity with the relevant series of standards ISO 14 040 – is if the improvement options, which can be deduced from the LCI, are perceived by the decision-maker as to redirect the material flows at stake into more sustainable paths.

From this functionalistic conception of LCA, this article develops a set of wood-specific requirements, an LCI of wood products has to fulfill to give adequate decision support under Central European conditions. These requirements serve as a basis for the evaluation of different allocation procedures in a case study related to the modeling of end-of-life scenarios in a product LCA of wood products. The case study evaluates how the recycling and incineration of a creosote-treated railway sleeper (*Am.* tie) are modeled according to various methodological propositions for the solution of the allocation problems related to recycling and final disposal. Case specific conclusions are drawn and the functionalistic conception of LCI is revisited.

1.1 Functionalistic conception of LCA

Establishing the life cycle inventory (LCI) of a product is an ambiguous task. Although guidelines and handbooks for conducting an LCA are available (e.g. ISO 14040 ff, [1]), various decisions during the setting up of the life cycle inventory (LCI) rely on subjective assumptions and choices. This is particularly true for allocations related to co-production processes and for the modeling of end-of-life scenarios such as recycling or waste incineration with co-generation of heat and/or electricity.

As has been elaborated in the last years [2–6], the influence of subjective elements cannot only be reduced to the scope and goal dependency of an LCA and to the assessment step. Subjective choices are also necessary in LCI whenever ma-

terial and energy flows cannot be attributed to a product in an unambiguous way. In such ambiguous decision situations, decision-makers' mental models and their value systems finally guide the setting up of the life cycle inventory of a product [5].

Many decisions during LCI require the use of mental models [7], refer to values or depend on the specific objectives, among them [5]:

- Distinction between products, co-/byproducts, and waste when allocating co-production processes
- Choice of an allocation factor for joint co-production processes
- Choice of an open-loop allocation procedure
- Selection criteria for substituted or additionally caused processes if system expansion is chosen to avoid allocation
- Handling of the (structural) ignorance about future processes, e.g. related to reuse and recycling

The product system as a model of the mass and energy flows 'causally' related to a product is a non-tangible theoretical construct. Thus, the LCI does not allow one to unanimously 'measure' the environmental interventions of a product by modeling, which is often implicitly assumed in methodological discussions; it 'only' allows the modeler to quantify the environmental interventions of a product with regard to his/her mental models and preset values (p.e. on the desirable 'sustainable' specific material and energy flows within technosphere). The reference to mental models and values can be made implicitly by using a 'standard' methodology or explicitly by selecting a methodological solution for its capacity to depict the decision-maker's mental models and values. This key issue has not been appropriately considered in the methodological discussion on allocation procedures so far.

Consequently, a major issue is thus to acknowledge the subjectivistic nature of the product system under study. Given:

- the complexity of material and energy flows within our socio-economic system;
- the simple model characteristics of an LCI – an a-temporal, spatially undifferentiated input-output model which does not consider (higher-ordered) interactions;
- the theoretical character of a product system and LCI

ambiguous decision situations – inherent to the above-mentioned modeling situation – can only be solved by referring to the decision-maker's (or modeler's) mental models, perspectives and values. Although there is no objectively right way of modeling a product system, there is at least a subjectively best way [5,6].

In the case of allocation, guidelines on LCA – and the series of standards ISO 14 040 ff. in particular – provide a structured, prescriptive approach for the modeling of a product system.

In the case of recycling – the primary focus of this paper – ISO 14041 acknowledges the fact that "several allocation procedures are applicable for reuse and recycling" (ISO 14041, chap. 6.5.4). This standard mentions several issue that need to be addressed when modeling reuse and recycling in LCA. Nonetheless, no criteria are established that would help the modeler to decide which of the many allocation procedures described in literature lead to the most adequate model.

The fact that methodological choices in LCA can have significant impact on the overall result and on the ranking of products assessed has often been analyzed [8,9]. A sensitivity analysis is recommended in ambiguous decision situations during the conduct of an LCA (e.g. ISO/EN 14041, chap. 6.5.2, point 3). But a sensitivity analysis can only provide insight into the relevance of a certain variable or methodological choice compared to the overall result. For decisions with far-reaching consequences on the result, requirements have to be fulfilled which determine the appropriateness and preferability of a given model structure or of a methodological alternative. Modeling decisions during the setup of an LCI should be based on an evaluation how well the alternatives represent the decision-maker's (or modeller's) mental models and values (see Section 2).

We have learnt from cognitive science that only if the decision-maker's mental models and pre-set (!) values are represented adequately in an LCI and LCA, there is a good chance that a decision-maker will gain ownership of the model and that the results of an LCA will become relevant in his/her decision-making process [5].

1.2 Post-consumer waste wood in LCA

The specific conditions of wood as a naturally grown, renewable material and its twofold nature as a material and fuel require some specific, interconnected methodological considerations, which are related to attribution and allocation in LCA. Among the topics to be considered are:

- The consistent handling of the C-uptake and of the embodied energy over the whole life cycle of a product [10–12];
- The combined combustion of post-consumer waste wood in municipal waste incinerators requiring the allocation of emissions to single fractions and the allocation of emissions from landfill [13];
- The handling of the material and fuel aspect of wood in comparative studies with non-renewable materials or energy carriers [11,12];
- The allocation of co-products typically generated throughout the wood processing chain from thinning, saw mill and wood industry requiring co-product allocation allowing material or energetic use;
- The allocation related to reuse, recycling, and thermal energy recovery.

This paper focuses on the question how reuse and recycling of post-consumer waste wood as part of the whole life cycle of a product should be modeled in a (comparative) product LCA. A secondary topic is the choice of an allocation factor used for the allocation of joint co-production processes. The comparison of different waste wood management systems as such is beyond the scope of this paper [14,15].

Allocation issues related to end-of-life scenarios, particularly recycling, have been discussed theoretically since the broader perception of LCA for the attributive [16–25] as well as for the change-assessing consecutive type of LCA [26–28]. This variety of methodological propositions provides the basis for the setting up of models that suit the criteria set up in Section 2.

For wood, several studies have been published on recycling of waste paper and cardboard [13,29–33]. The allocation procedures developed in the context of waste paper recycling are often not transferable to post-consumer waste wood, as parameters such as the number of subsequent uses or the recycled material content are normally not determinable for post-consumer waste wood. Other procedures are developed for the assessment of end-of-life systems as such and are not intended to be used in product LCA.

For post-consumer waste wood, no systematic research has been conducted so far on the influence of different mental models and values on allocation assumptions and modeling related to end-of-life scenarios in (comparative) product LCA. Furthermore, no systematic evaluation of different allocation procedures for end-of-life scenarios regarding their suitability for LCA of wooden products has been made. Almost no experience exists with value-based approaches to the allocation problems in LCAs of wooden products. These gaps were addressed in a research project within the European COST Action E9 'Life Cycle Assessment of Forestry and Forest Products', on which this paper is based ([34], where also detailed numerical results can be consulted).

2 Requirements for Life Cycle Inventories of Wood Products

LCA is a decision-support tool. It is chosen by a decision-maker because he/she considers the procedure and resulting model as useful and beneficial to describe the environmental impacts of a product. On the other hand, the descriptive power of every tool has its limitations in a complex context such as our socio-economic system. Mental models – conceptualizations of aspects of our real world – have to be applied and value choices have to be made to define the life cycle of a product. The addressing of the decision-maker's mental models and values is paramount for an LCA suiting the decision making process [35,36].

Apart from some general requirements derived from decision analysis, a 'good model' has to fulfill such as completeness, operationability, decomposability, transparency or actor-basedness or site- and case-specificity [37–41] some particular characteristics are relevant in the context of LCA. An LCI of a product that supports the process of rational decision-making best – and thus the most 'descriptive' and most adequate LC-model of a product – respects [5,6]:

- Material- and market characteristics of the materials involved in the definition of the life cycle model of a product;
- The decision-maker's mental model of the organizational principle of the socio-economic system;
- The decision-maker's attitude towards risk when modelling future processes.

Furthermore, it provides:

- Improvement options that are in line with the material- and context-specific management rules for the sustainable material- and energy flows within technosphere.

Having in mind the scope and descriptive power of LCA, the following management rules for a sustainable use of wood can be derived from the current discussion on a sustainable use of wood in Central Europe. They should be adequately addressed in LCAs of wooden products [42]:

1. Efficient and effective processing of wood as material in wood industry and in usage [43–52].
2. Renunciation of chemical wood protection where possible (*e.g.* by constructive means) and careful selection of additives like foils, glues, coatings, etc. (see also point 4) [46,48,52–54].
3. Production of products that can easily be disassembled thus providing single-material fractions for easy recycling and incineration in appropriately equipped plants [43,46,48,51,52,54,55].
4. Maintenance of the incineration potential for the substitution of non-regenerative fossil fuels [45–47,56–61].
5. Maximization of the amount of wood carbon stored in long-term applications such as buildings taking into account the effective and efficient use of wood (point 1) [46,59,61–63].

Decisions in the inventory step related to the attribution (and 'allocation') of environmental interventions to the product under study should be made in accordance to the above-stated characteristics and principles. Only in this way, the outcomes of an LCA – and thus its underlying models – become relevant for the decision-maker in a way that they influence his or her action.

In the following case study, a systematic evaluation of allocation procedures is made based on the requirements for LC-models and wood-specific aspects outlined above. This should provide a sound line of reasoning for the preferability of methodological choices for the modeling of post-consumer waste wood in (comparative) product LCA.

3 Recycling or Incineration of a Railway Sleeper Made from Beech

This case study aims at evaluating different approaches to the modeling of two end-of-life scenarios for beech wood railway sleepers as last life stage in a (comparative) product LCA:

- Incineration of the railway sleeper in an incineration plant with co-generation of electricity and thermal energy;
- Recycling of the railway sleeper as constructive element in landscape architecture.

The underlying LCI and economic data are taken from an existing LCA-study on railway sleepers in Switzerland [64]. The end-of-life scenarios are generic, reflecting the current situation in Switzerland and are selected for the methodological purpose of this paper.

The allocation procedures as modeling alternatives for the end-of-life scenarios represent different lines of reasoning within the LCA-community (Section 3.2).

Modeling of end-of-life scenarios can depend on decisions related to the allocation of co-production processes made in previous life cycle steps of a product, such as forestry, transports from forestry or sleeper production. To assess this influence, limited life-cycle models for the product railway sleeper are set up in order to evaluate the overall effect of the allocation procedures under investigation (Section 3.3).

The evaluation is made based on the descriptiveness of a modeling alternative with respect to the material and market characteristics of wood, the logic of process-specific decision-making and planning, and the wood-specific management rules for its sustainable use (see Section 2).

3.1 Functional unit and reference flow

The functional unit considered is the creosote-treated wooden part of the railway sleeper made from beech for Swiss standard gauge railway tracks (measures 2600 × 260 × 150 mm). The track bed and its construction, maintenance and disposal as well as metallic auxiliary materials (accessories for securing the rails) are omitted for the purpose of this case study.

The reference flow focuses on the processes possibly affected by allocation procedures used for the modeling of the two end-of-life scenarios. All other mass and energy flows are omitted for the sake of simplicity. Possible recycling of used railway sleepers as railway sleepers in areas with lower strain are also disregarded for the sake of simplicity of the case study (for details, see [64]).

Fig. 1 illustrates the main processes of the reference flow. The allocation problems I and II as part of modeling decisions related to the whole life cycle of the sleepers are described in Section 3.3.1.

3.2 Modeling the end-of-life scenarios

After service life railway sleepers are removed from the railway track. Currently, two scenarios exist in Switzerland: recycling or incineration. While the (monopolistic) owner of used railway sleepers can sell them for about 10.- € per piece for uses in landscape architecture, incinerating them in a waste incinerator costs him an average of 10.- € per piece [65]. While a railway sleeper used in landscape architecture is assumed to rot completely without using the embodied energy of wood and creosote, this potential can be used in waste incinerators if thermal energy and/or electricity is co-generated.

3.2.1 Allocation problems and procedures considered

The recycling scenario as a constructive element in landscape architecture and the incineration scenario with co-generation of thermal energy and electricity pose different modeling problems. Among the questions that can arise concerning the allocation related to recycling or incineration of railway sleepers – and which are reflected in the selected allocation procedures – are:

- Should the railway sleeper used in landscape architecture carry environmental burdens from sleeper production?
- Should environmental burdens from the use of the sleeper in landscape architecture partly be attributed to the railway part, as the secondary use fulfils waste disposal function?
- Should substitution effects be considered when using the railway sleeper in landscape architecture instead of concrete elements?
- Should substitution effects be considered for the production of heat and/or electricity when incinerating the sleeper, e.g., the substitution of thermal energy and/or electricity of other plants?
- Should credits be given for the production of thermal energy and/or electricity when incinerating the sleeper, e.g., subtracting the electricity generated from electricity used for production while attributing the environmental interventions related to incineration to the sleeper (closed-loop assumption for electricity)?
- Should the environmental opportunity effects (opportunity 'cost') be considered when wood is used in a way, which inhibits thermal energy production and the substitution of fossil fuels correspondingly?
- Should incineration be considered a bi-functional process providing waste treatment and generation of thermal energy and/or electricity, when attributing part of the incineration process to the sleeper and part to the generation of thermal energy and/or electricity?

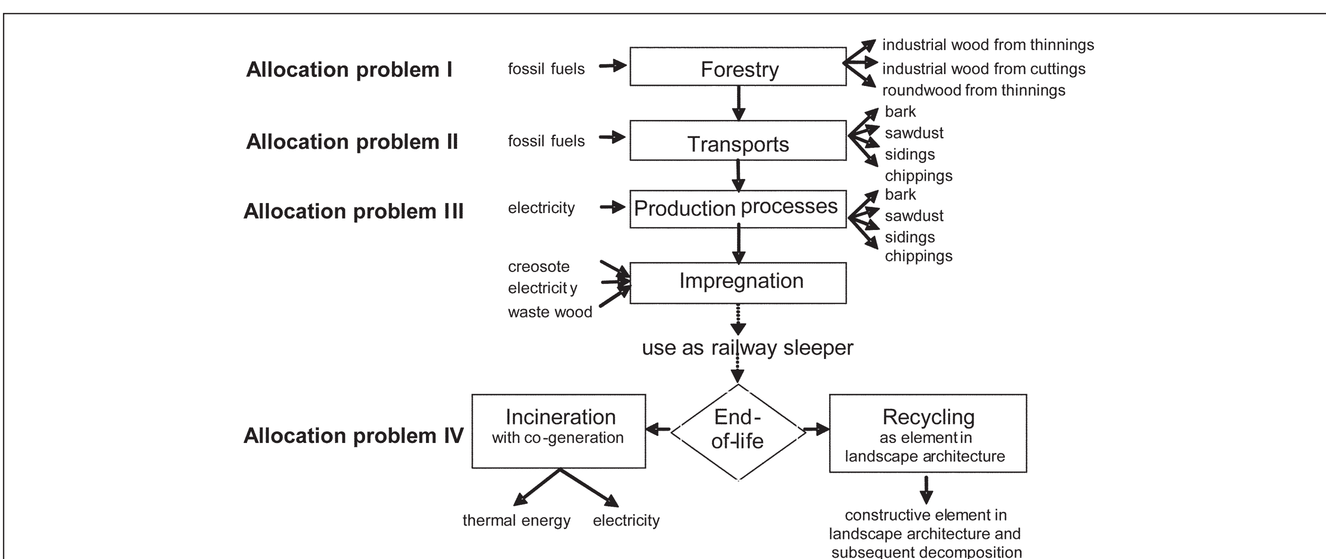


Fig. 1: Model of the reference flow

Several allocation procedures are discussed as modeling alternatives for the recycling or incineration of the sleeper. It has to be stressed that the allocation procedures lead to differing product systems in dependency of the mental models and values underlying the allocation procedures. The purpose of this evaluation is to evaluate the 'descriptiveness' of the resulting product LCI regarding particularly the wood-related requirements established in Section 2.

The following mental models and values underlie the allocation procedures used for the modeling of the recycling of railway sleepers as constructive material and landscape architecture:

Cut-off (LSA): The primary aim of the railway sleeper production is the production of railway sleepers. Hence, all environmental interventions related to production processes are attributed to the sleeper. If anybody takes the sleeper for further uses, the sleeper use does not carry any environmental interventions related to its disposal; the secondary user gets the used sleeper as element of landscape architecture (LSA) free of environmental burdens [22,24].

50/50: the uses of the railway sleeper in the railway track and as element of landscape architecture are part of the same life cycle of the impregnated beech wood. Correspondingly, all environmental interventions related to the raw material acquisition and production of the sleeper (as shaping and impregnation are also a precondition for the use of the sleeper as element in landscape architecture) are equally distributed to the two uses. Rotting of the sleeper is assumed as the end-of-life scenario for the second use of the sleeper; as wood carbon is considered a material-inherent property, no additional emissions are allocated to the first life cycle as biogenic carbon is disregarded in these calculations (this reasoning also applies to other substitution based procedures) [22].

Value-corrected substitution (VCS): The production processes provide two products in a cascade. Allocation is made based on the relative price difference. The environmental interventions (EI_1) allocated to the sleeper as product 1 are calculated from the total environmental interventions of the railway sleeper production (EI_T) as follows:

$$EI_1 = EI_T * \frac{p_1 - p_2}{p_1} \tag{1}$$

with

p_1 = market price of product 1 (only material under consideration)

P_2 = market price of product 2 (only material under consideration)

The second use, the railway sleeper as element in landscape architecture, carries the remaining environmental interventions [5,9,66].

Opportunity 'cost' of inhibiting thermal energy recovery (Op-cost): The recycling of railway sleeper as element in landscape architecture inhibits thermal energy recovery. The potential of (creosote-treated) wood for substituting fossil energy carriers is not used. Hence, the avoided incineration and the production of an equivalent amount of thermal energy and electricity are accounted for [11,31,67].

Substitution of concrete element production (Sub-con): The railway sleeper provides two functions, a) the fixation of the railways, and b) the retention of soil in landscape architecture. It is assumed that a concrete element would otherwise have fulfilled function b). Hence, the production and disposal of an equi-functional concrete element is subtracted from the inventory of the railway sleeper production processes in order to obtain a mono-functional model [11,31,67].

Opportunity 'cost' and substitution effects considering material and energy aspects of wood (Op-cost MEA)*:* The last approach is a combination of the opportunity 'cost' considerations on the energy-side (Op-cost) and the avoided-burden considerations on the material side (Sub-con) (combining arguments by [11,31,67]).

The following mental models and values underlie the allocation procedures used for the modeling of the disposal of railway sleepers in a waste incinerator with co-generation of heat and electricity:

Cut-off (WI): Waste incineration (WI) is considered a waste treatment process (as one has to pay for the incineration). Hence the wooden sleeper gets all environmental interventions related to waste incineration [22,24]. One could of course argue that the co-generation of thermal energy and/or electricity should also be taken into account. This is done by the Strict co-product allocation described further down.

Closed-loop: The incineration processes are considered a part of the life cycle model of the railway sleeper. The environmental interventions are allocated to the sleeper, whereas the generated electricity is subtracted from the life cycle inventory of the sleeper. The thermal energy generated is not considered any further as the sleeper production facility is assumed not to be connected to the district heating system ('open-loop') (ISO/EN 14041, chap. 6.5.4).

Strict co-product allocation (SC-PA): Waste incineration is considered a bi-functional process providing waste treatment and generation of thermal energy and/or electricity. Incineration is considered waste treatment as long as the market value of the impregnated wood in treatment is negative. The process is allocated to the thermal energy and/or electricity produced as soon as the market value of the treated material gets positive. Hence, attribution is made partly to the sleeper, partly to the generation of thermal energy and/or electricity taking the waste incineration plant as a black box. The allocation factor is calculated as the portion of the disposal cost compared to all the revenues of the process, i.e. the sum of the market prices of thermal energy and electricity and the disposal cost [1,68].

Substitution of energy production (Sub-en): The railway sleeper production provides two functions: a) the fixation of the railways, and b) the generation of a fuel. A substitution for function b) is subtracted in order to obtain a mono-functional model. It is assumed that the waste treatment process provides thermal energy and or electricity, which substitutes for the respective products from the most expensive existing plant. This assumption is true for Switzerland, where the landfilling of burnable waste is prohibited; this is not necessarily true for countries with a shortage of incin-

Table 1: Lines of reasoning considered for the modeling of the end-of-life scenarios 'incineration with co-generation' and 'reuse as element in landscape architecture'. Note that these descriptions are case-specific and not generic ones

Element in landscape architecture	
Cut-off (LSA)	± 0 (2nd life cycle carries burdens from recycling)
50/50	– ½ wood processes incl. impregnation; 2 functions
VCS	$(p_1 – p_2)/p_1$ * (wood processes incl. impregnation)
Op-cost	+ fossil energy + electricity – incineration process
Sub-con	– concrete element and its disposal
Op-cost MEA	+ fossil energy + electricity – incineration process – – concrete element and its disposal
Incineration with co-generation	
Cut-off (WI)	+ incineration process (no credits for energy)
Closed loop	+ incineration process – electricity generated; (heat -> open loop)
SC-PA	+ incineration process * $(p_{waste\ treatment}/(p_{waste\ treatment} + p_{electricity} + p_{heat})$
Sub-en	– fossil energy – electricity + incineration process
Op-cost MEA	– fossil energy – electricity + incineration process + + concrete element and its disposal

eration capacity. In such a case, the incineration of other waste fraction would be substituted for without further consequences for other thermal energy or electricity generators [27,30,32]. So in this case study, the production of thermal energy and/or electricity in an alternative plant is subtracted from the inventory of the railway sleeper processes [11,31,67].

Opportunity 'cost' and substitution effects considering material and energy aspects of wood (Op-cost MEA): The reciprocal reasoning on substitution effects as made in the above Op-cost MEA is also feasible if the sleeper is burnt in an incineration plant. In this case, the production of an equifunctional concrete element and the incineration of the sleeper are attributed. On the other hand, the average amounts of electricity and thermal energy generated in an alternative plant are subtracted from the LC-inventory of the railway sleeper (see also Op-cost MEA above).

Table 1 summarizes the scenarios under consideration. Note that the descriptions reflect the case-specific assumptions. For this reason, the descriptions do not necessarily include all elements of the generic allocation procedures. This is particularly true for the rotting of the sleeper in landscape architecture, which is considered not to have any environmental impacts apart from the emission of biogenic CO_2 (disregarded in these calculations).

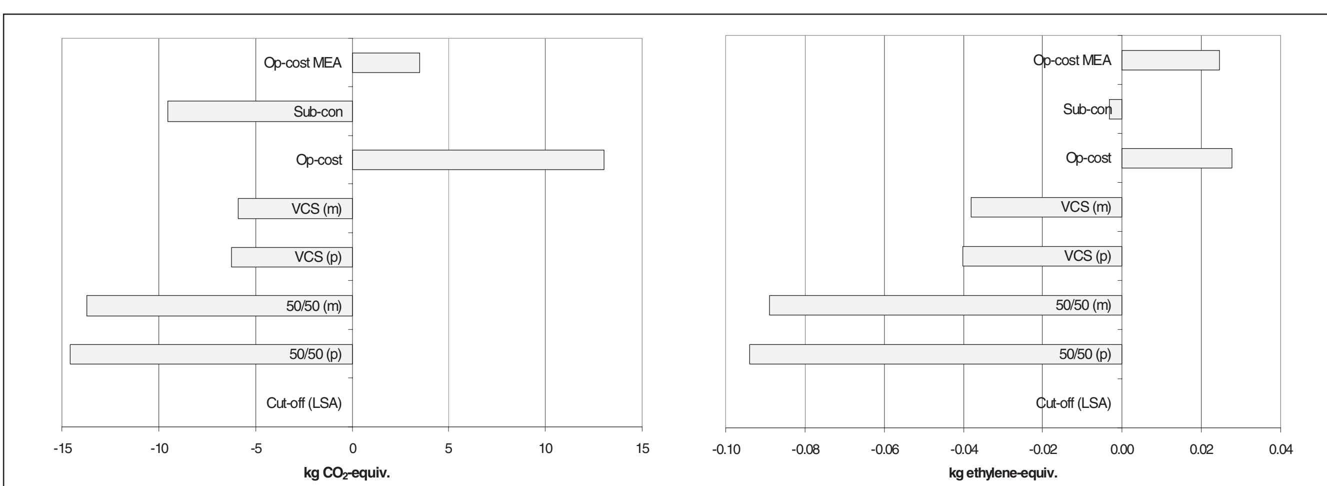
3.2.2 Scenario specific results and interpretation

For the sake of the methodological discussion, the different modeling alternatives for the two end-of-life scenarios as described in Table 1 are compared first without considering the whole product system. The different modeling alternatives are assessed with the 'effect-oriented classification' according to [69] (CML-method), updated according to [70]).

For the modeling of the recycling variant of railway sleepers as constructive material in landscape architecture, the results of the approaches differ for each of the environmental impact categories because of the different types of processes included in the product system. The results of the impact assessment can be classified in two groups: The potential contributions to greenhouse effect show the same ranking of the modeling alternatives as the potential contributions to eutrophication; the other impact categories show the same ranking for all modeling alternatives. **Fig. 2** and **Fig. 3** illustrate the arbitrarily chosen impact categories 'greenhouse effect' and 'photosmog' for being representative for the two groups of rankings.

Fig. 2 and Fig. 3 show that three of the six allocation procedures lead to negative environmental impacts.

The Cut-off procedure does not add or subtract any environmental interventions to the product system of the railway sleeper.



Figs. 2–3: Potential contributions to the greenhouse effect and to photosmog of different allocation procedures used to model the recycling of railway sleepers as constructive material in landscape architecture (per sleeper). (p) allocation based on proceeds; (m) allocation based on mass

The allocation procedures 50/50 and VCS redistribute environmental interventions partly to the secondary use. The choice of the allocation factor (proceeds or mass) does not have a significant impact on the results of these alternatives.

The Sub-con procedure accounting for the substitution of a concrete element leads to negative environmental interventions. But the assumed substitution of a concrete element is only part of the avoided or additionally caused environmental interventions related to the recycling of the railway sleeper. A complete 'avoided-burden' approach would also consider the avoided incineration processes and account for the thermal energy and electricity processes that would result from the incineration of the sleeper (see Op-cost MEA).

The Op-cost procedure accounting for the opportunity 'costs' related to the energetic aspect of wood leads to further environmental impacts attributed to the railway sleeper; the avoided incineration of the sleeper does not compensate the additional impacts for thermal energy and energy production. But as the Sub-con procedure focuses on the material aspect of wood, the Op-cost procedure only considers part of the substitution effects.

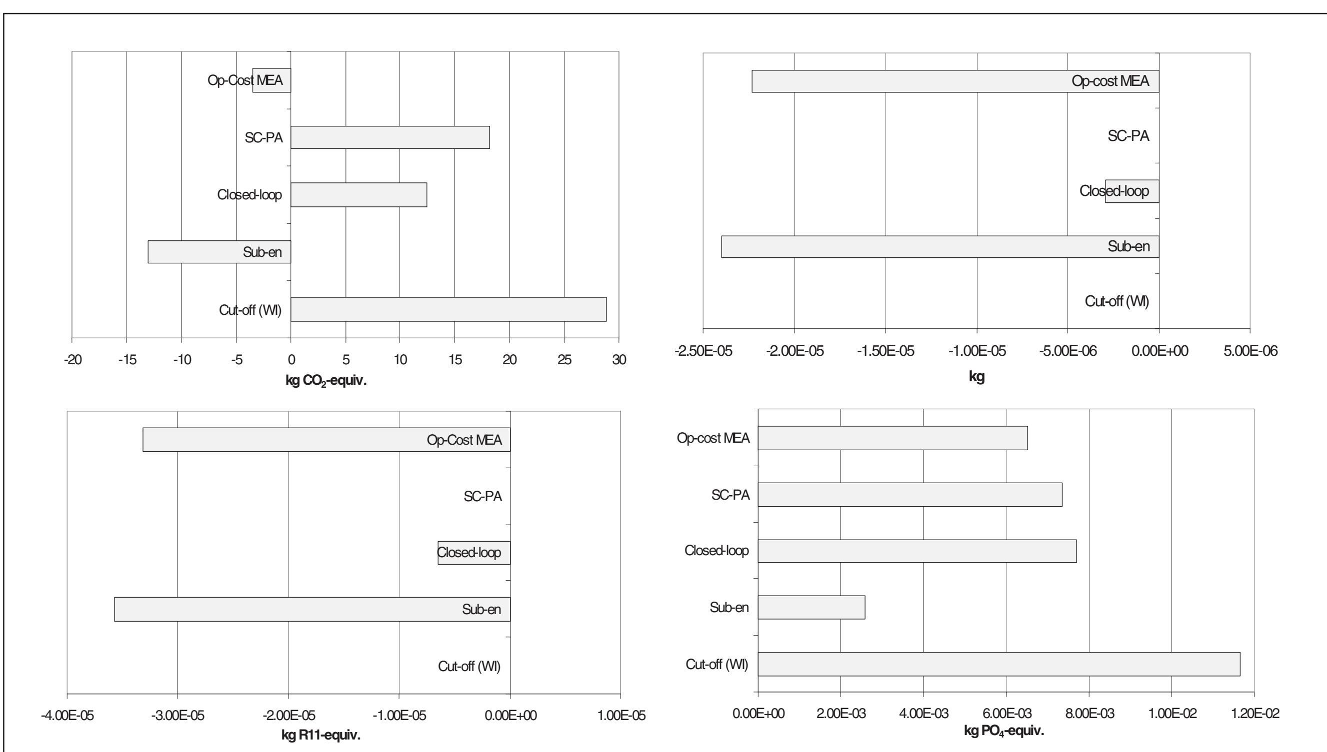
The result of the Op-cost MEA procedure is the sum of the Op-cost and the Sub-con procedure; it results in additional opportunity 'costs' to be attributed to the sleeper if the sleeper is used as element in landscape architecture.

For the modeling of the disposal in a waste incinerator with co-generation, the following impact categories show equal rankings of the modeling alternatives:

- Greenhouse effect, acidification, photosmog, human toxicity, and ecotoxicity water
- Ozone depletion and the use of abiotic resources
- Eutrophication
- Ecotoxicity soil

Again, the representatives of the four rankings are chosen arbitrarily (**Figs. 4–7**). The results of the impact assessment of the incineration scenario are ambiguous. Except for the Cut-off (WI) procedure, all allocation procedures lead to both positive and negative environmental interventions to be attributed to the railway sleeper. Only the Cut-off (WI) procedure accounts solely additional environmental interventions. This result is not surprising given the differing types of processes and different ways of accounting considered in the different allocation procedures. Still, some comments can be made with regard to the assumptions underlying each allocation procedure.

The Cut-off (WI) allocation procedure considers the incineration process as pure waste treatment. The co-generation of heat and electricity in modern Swiss municipal waste incineration plants is disregarded. This assumption is highly questionable given the state-of-the-art character of these technologies in almost all Swiss (municipal) waste incinerators. Additionally, no incentive is given to a decision-maker to deliver his sleepers to an incineration facility with co-generation. This would be against the management rule for the sustainable use of wood claiming thermal energy recovery for the substitution of non-renewable energy carriers.



Figs. 4–7: Potential contributions to greenhouse effect, ecotoxicity soil, ozone depletion and eutrophication of different allocation procedures used to model the disposal of the wooden railway sleeper in an incineration plant with co-production of thermal energy and electricity (per sleeper)

The Sub-en allocation procedure focuses on the potential of thermal energy recovery and the substitution of non-renewable energy carriers. But the material aspect of wood and the related substitution processes are disregarded. This omission can be an advantage if the determination of hypothetical substitutes for the burnt wooden sleeper is considered unsuitable, e.g. for the risk-aversion of the decision-maker. On the other hand, the 'picture' is incomplete if the material aspect of wood is disregarded; no recommendations can be made with regard to the adequacy of recycling or incineration of wooden sleepers.

The Closed-loop procedure giving credits for the generation of electricity ('closed-loop') and disregarding thermal energy production ('open-loop') provides an inconsistent model. There exists no causal economic or technical reason justifying this arbitrary different handling of electricity and thermal energy production.

The Strict co-product allocation procedure (SC-PA) provides a consistent attribution of the incineration processes to the sleeper as well as to the electricity and thermal energy generated. Inherent to this procedure, the SC-PA does not consider any opportunity 'cost'.

The Op-cost MEA procedure accounting for the substitution effects and opportunity 'costs' related to the material and energy aspect of wood provides results reciprocal to the recycling of used railway sleeper as element in landscape architecture. The Op-cost MEA is the only allocation procedure that allows statements on the usefulness of recycling versus incineration with co-production of electricity and thermal energy in a product LCA. Interesting enough, incineration with co-generation is favorable to the greenhouse effect (supporting point 4 in Section 2) and to various other impact categories under the assumptions of this study. However, it leads to additional potential impacts to eutrophication. The same information can of course be gained by using two models, one model based on the Op-cost approach, the other one on the Sub-en approach. However, two models are not handy in comparative product LCA.

3.2.3 Context specific evaluation of the allocation procedures

The Cut-off procedures give preference to the recycling of the sleeper although opportunity 'costs' are positive for this alternative, as it makes fossil fuel substitution impossible (Op-cost MEA). This is not in line with point 4 for the sustainable use of wood of Section 2. In addition to that, the economic value of a railway sleeper is not determined freely as there exist in fact two market prices for it, one for resale and one for disposal. This implies that depending on the end-of-life scenario different system boundaries are set, which brings additional uncertainty into modeling if the secondary use is not pre-set. The Cut-off procedure can lead also to severe discussions in comparative studies when, e.g., elements for landscape architecture are assessed with LCA. According to the cut-off philosophy the recycled railway sleeper would be available with no environmental burden attributed to it, although the cutting of wood and especially the impregnation are preconditions for this application. Representatives of other materials would possibly argue strongly against this line of reasoning and its underlying mental models and values. All in all, the Cut-off procedure does not address the management rules of a sustainable use of wood and the current material and market characteristics of waste wood in a product LCA of railway sleepers in an adequate way.

The 50/50 procedure assumes equal functionality ('value') of the function of a railway sleeper as railway sleeper itself and as element of landscape architecture. This mental model is most probably not shared by many people. Note that there exists another rationale for the 50/50 procedure in marginal (consecutive) LCA, which is based on equal price elasticities of primary and secondary material (see [27]). But consecutive LCA are not the scope of this paper.

Also the application of the value-corrected substitution faces considerable disadvantages. For the applicability of the value-corrected substitution, primary production processes (and final disposal processes) should be equal for each type of products originating from the resource, and it should be plausible that recycled material substitutes primary production processes. Here, primary production processes of equi-functional wooden elements for landscape architecture – though they exist – would certainly not correspond to the production and impregnation processes of railway sleepers. It is much more likely that salt-treated wooden palisade elements or even a concrete element would be use instead of a used railway sleeper. This contradicts the first of the above-mentioned points. So, production processes which are definitely caused by the use of the railway sleeper as railway sleeper itself are attributed to the secondary use. Furthermore, substitution effects will probably not occur within the wood chain but will affect other materials (contradicting the second point). Hence, the basic assumptions, on which the VCS is based, are not consistent with the material and market characteristics of used wooden sleepers.

The Closed-loop procedure applied to the incineration process treats thermal energy and electricity co-generation inconsistently. This could only be justified if the aspect should be stressed that electricity is a more valuable form of energy as it can be easily be stored and transported. This does not make sense in the case of densely populated areas with thermal heat demand, such as Switzerland.

If opportunity 'costs' should be considered – and point 4 of Section 2 implies this – real and 'lost' substitution effects must be considered for both the energy and material aspects of wood. This is done by the Op-cost MEA procedure. All other procedures relying on substitution effects or opportunity 'cost' (Op-cost, Sub-con, Sub-en) only cover part of the real and hypothetical substitution effects. Hence, they can possibly recommend 'improvement options', which are not in conformity with the management rules of a sustainable use of wood outlined in Section 2. A difficulty consists in determining the substitution effects related to the material aspect of wood [11]. Here, consensus has to be achieved among the stakeholders of an LCA. The Op-cost MEA procedure is the only procedure that allows statements on the usefulness of recycling compared to the incineration of wood in a product LCA (if one does not build up two separate

models depicting each one possible substitution – which would contradict the criterion that a model has to be complete, see Section 2).

For the interpretation of the results, it should be kept in mind that assumptions made for the modeling of the concrete element are rough approximations. Furthermore, assuming a concrete element to substitute for a railway sleeper in landscape architecture is a plausible best guess. In addition to that, prices for incinerating railway sleepers vary considerably for each (municipal) waste incineration plant [55]. The study used Swiss average data. These limitations seem justifiable in view of the methodological purpose of this paper.

3.3 Effects on the whole life cycle

In this Section, the significance of the choice of an allocation procedure for end-of-life scenarios as last step in a product life cycle is investigated. For this purpose, partial life cycles are modeled 'from cradle to grave' for the recycling and incineration scenario for the railway sleeper.

3.3.1 Scenarios selected

For the following considerations, life cycle models are set up for some of the modeling approaches discussed in the previous Section (see Table 1). Allocation problems encountered in previous (up-stream) processes (see also Fig. 1) are solved aiming at over-all consistency of the whole life cycle model considering the underlying assumptions of each of the allocation procedures [34,71]:

- Forestry processes are allocated to industrial wood and roundwood independently of its time of harvest ('over-all') based on volume or relative share of proceeds;
- Transports of the roundwood for sleeper production from the forest to the production site are allocated to all the products generated during processing of the log on a mass-basis or based on the relative share of proceeds ('over-all');
- Production processes are subdivided in trimming, debarking, conversion, sorting, and mechanical processing and allocated based on mass (moisture content mc = 0) or relative share of proceeds;
- End-of-life scenarios are modeled according to allocation procedures outlined in Section 3.2. The approaches treated further are Cut-off, VCS, the Op-Cost MEA, and the SC-PA.

The Cut-off procedure is included also as a reference because it represents the way many product LCAs are currently conducted. For the Cut-off procedure, all environmental interventions of transports and production are allocated to the sleeper. Consequently, also the forestry processes (119 kg wood; mc = 0%) are fully accounted for the sleeper.

The following life-cycle models are combined as illustrated in **Table 2**.

For the sake of simplicity several aspects are not covered by this partial reference flow. For instance, transport processes related to recycling and incineration activities would also be subject to allocation procedures similar to the transports from forestry to sleeper production. Furthermore, other materials such as metallic auxiliary materials for securing the ties to the sleepers or the track bed are not considered in the calculations.

3.3.2 Results and interpretation

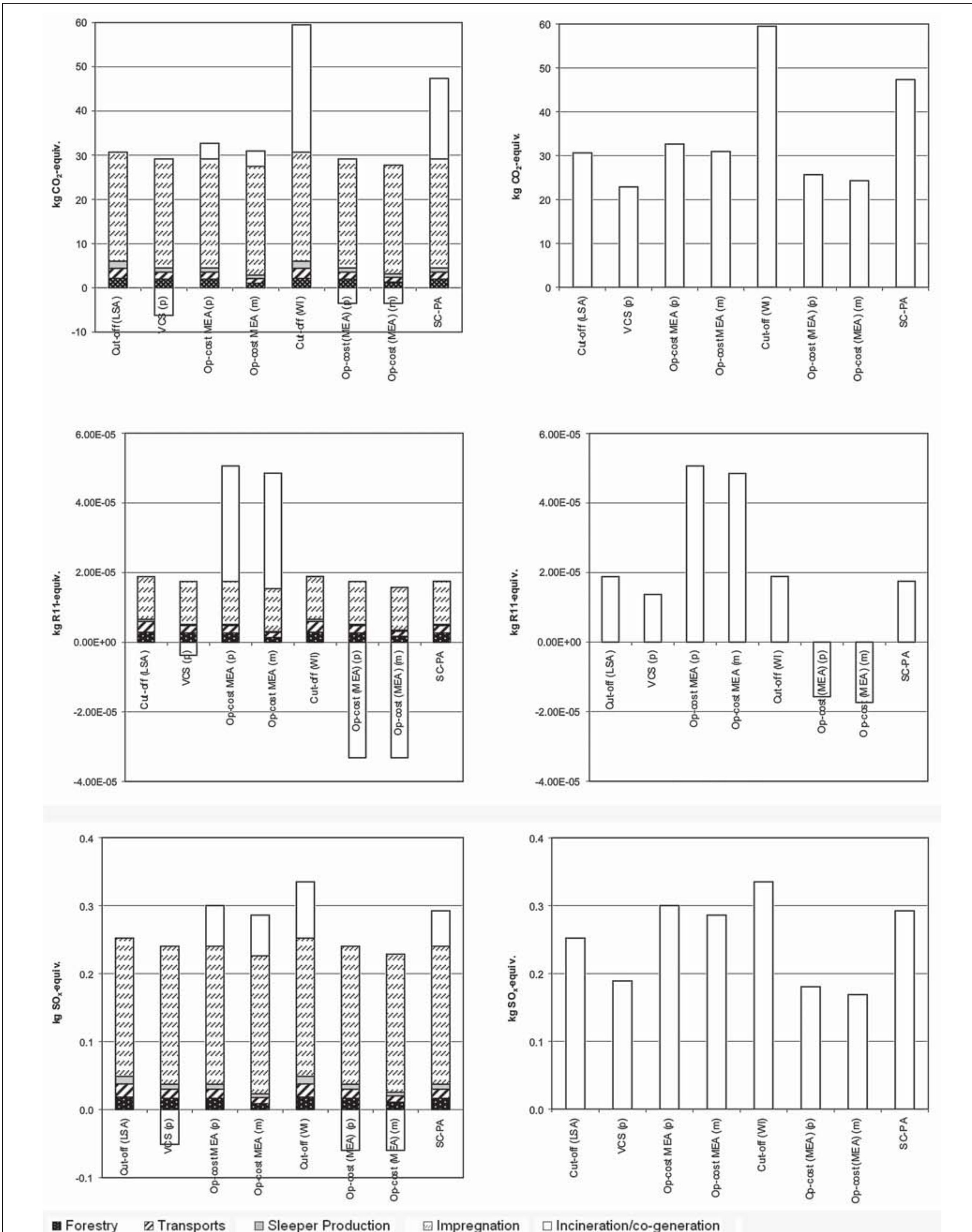
The life-cycle models are assessed based on the 'effect-oriented classification' evaluation method according to [69] (CML-method), updated according to [70].

Figs. 8–13 illustrate the outcome of the impact assessment selecting several impact categories on an arbitrary basis. On the left side, the contributions are listed without recalculating net effects; the net effects are illustrated on the right side.

Table 2: Life cycle models combined for the recycling scenario and the incineration scenario with thermal energy and electricity co-production

	Material use				Energetic use			
	Cut-off (LSA)	VCS (p)	Op-cost (MEA) (p)	Op-cost (MEA) (m)	Cut-off (WI)	Op-cost (MEA)	Op-cost (MEA) (m)	SC-PA
Forest [1]	Over-all, volume	Over-all, proceeds [2]	Over-all, proceeds [2]	Over-all, volume [3]	Over-all, volume	Over-all, proceeds [2]	Over-all, volume [3]	Over-all, proceeds [2]
Transports	All-to-sleeper	Over-all, proceeds	Over-all, proceeds	Over-all, mass	All-to-sleeper	Over-all, proceeds	Over-all, mass	Over-all, proceeds
Production	All-to-sleeper	Step-by-step, proceeds	Step-by-step, proceeds	Step-by-step, mass	All-to-sleeper	Step-by-step proceeds	Step-by-step mass	Step-by-step proceeds
Impregnation	all	all	all	all	all	all	all	all
Recycling	Cut-off (LSA)	VCS	Op-cost (MEA)	Op-cost (MEA)				
Incineration					Cut-off (WI)	Op-cost (MEA)	Op-cost (MEA)	SC-PA

[1] using input quantities of wood to the production processes (119 kg, mc=0%) which are reallocated according to the allocation rules applied to production processes and/or final disposal
[2] redistributed according the allocation procedure applied to production processes
[3] redistributed according the allocation procedure applied to production processes



Figs. 8–13: Impact assessment of different life cycle models for the recycling or incineration of a railway sleeper from beech resulting from different allocation procedures: greenhouse effect, ozone depletion, acidification (left: absolute contributions, right: net effect; per sleeper)

For all impact categories, the effects are mainly caused by the impregnation processes (the production of creosote) and by the end-of-life processes. Transport from forestry to the production site of the sleeper is of secondary importance (in case of wood produced in Switzerland); electricity generation used in the sleeper production and in forestry processes is insignificant in all impact categories.

The effects of different allocation procedures can be ranked more or less clearly. For the recycling alternative, the life cycle with the VCS applied scores generally lower than the widely used modeling approach used in the Cut-off (LSA) alternative. Considering opportunity 'costs' (Op-Cost MEA) for the recycling of the sleeper leads to higher environmental impacts for all impact categories, except eutrophication.

For the incineration alternative, the life cycle with the Cut-off (WI) procedure scores highest for all the environmental impact categories considered. The procedure considering opportunity 'cost' and substitution effects always (Op-Cost MEA) leads to the lowest environmental impacts attributed to the railway sleeper if the sleeper is incinerated. The strict economic allocation procedure (SC-PA) leads to environmental interventions ranking in between the Cut-off (WI) procedure and the Op-Cost MEA procedure.

Note that the Cut-off procedure favors recycling of the sleepers as landscape element whereas the calculations based on the opportunity-cost procedures recommend the incineration with co-generation of thermal energy and energy. As the Cut-off procedure does not adequately depict sustainable management rules for wood and causalities within the wood chain, the Cut-off procedure leads to misleading recommendations.

The choice of mass or proceeds as allocation factors does not have a significant impact on the result for the Op-Cost MEA procedure.

The choice of the strict economic allocation procedure affecting mainly the end-of-life phase has significant impact on the results.

4 Conclusions and Outlook

The following methodological conclusions can be drawn from the case study for the modeling of end-of-life scenarios in wood product LCA:

- Considering (direct) substitution effects and (indirect) opportunity 'cost' are necessary components for the consistent modeling of end-of-life scenarios as last phase of the life cycle in attributive product LCA (if one agrees to the management rules for a sustainable use of wood outlined in Section 2). Only if substitution effects and opportunity 'cost' are considered in product LCA, statements on the effects and usefulness of recycling can be made. The way, how substitution effects and opportunity 'cost' are taken into account, depends on values and basic assumptions, e.g. on the role of market values or on the national characteristics of post consumer processes.
- Both the material and energy aspects of wood and the related substitution effects and opportunity 'costs' should be considered during the modeling of end-of-life scenarios as last phase in product LCA if the management rules for a sustainable use of wood of Section 2 should be addressed. These management rules are under development and may alter temporarily and between different contexts.
- The wood-specific principles combined with the general requirements for LC-models (Section 2) provide a consistent methodological guidance for the evaluation and pre-selection of allocation procedures in LCAs of wooden products. Still, they do not allow for an unambiguous determination of an allocation procedure as the underlying values are always disputable.
- Several co-product allocation procedures are applicable for different life cycle steps within the same LCA. The allocation procedure selected for each step widely depends on the decision-maker's mental models on the material and market characteristics, the purpose of the study as well as on the specific planning and decision structure assumed for the processes to be allocated.
- Given the specific considerations related to the modeling of post-consumer wood, it can be assumed that no generic allocation procedure is definable that would adequately depict the material and market characteristics of all materials available as well as the specific decision logic for each of their life cycle steps.

However, mental models, values and assumptions about priorities in the context are always subjective and depend on the historical circumstances. What might have priority in Switzerland does not necessarily hold true in another country. For the acceptance of an LCA, stakeholder involvement and agreements are essential for the acceptance of LCA results [72].

This paper promotes a functionalistic conception of LCA. This implies that the initially formed goal – for example the definition of desired 'sustainable' specific material and energy flow patterns – is crucially inherent in many modeling decisions that affect the final result. The presented goal-oriented approach, however, provides an LCI model of a product that meets the needs and the mental models of the decision maker. Thus it allows to draw consistent conclusions for the backward planning of improvement options, hopefully not only with respect the decision-maker's mental models and values [5,73–75], but also for real decisions.

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